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Information Nesting in Configural Interfaces for Process Control

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Abstract Gibson's (1979) theory on direct perception forms the basis of an ecological approach to interface design. The paper argues that interfaces for complex dynamical systems should seek to represent the system constrains identified by system engineers in an integrated configural display form, that allows for a direct perception of the invariant system behavior from display geometries changing according to incomming process data. Seven principles for the nesting of information in a configural fashion are suggested. The application of the principles is illustrated with a display sketch from a conventional power plant and further arguments for the principles is given in a general discussion.

In particular, the configural interface should integrate information on the system evolution over time, the objective clock time and a symbolic representation of the system functions. This integration is achieved in a new display format, the time tunnels, revealing process invariants and changes as symmetry or asymmetry in figural patterns over depth. In an outlook for the future it is suggested, that the new techniques emerging within virtual media environments may be used to achieve a natural perspective on process displays, changing with the head movements of the observer.

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1 Introduction

The control tasks in modern, high technology systems are multidimensional, requiring coordinated manual and automatic regulation of interdependent parameters. If the operator was only supported with a »one measurement - one indication«-displays (Goodstein, 1981), coordination would depend on his ability to understand the multi-variability of the system, the inter-dependencies of the parameters, and the interactions between manual and automatic controls. Because even minor malfunctions are potentially hazardous, the operator's understanding must develop without trial-and-error-learning. This seems to be an almost impossible learning task and, given the inevitable complexity of the system dynamics, the only solution to the control problem is to structure the **single data** as **goal relevant information.** Whenever data visually combines as a group with the new quality of relating to a meaningful task in the environment, this is more than a simple sum of data and will be called information (cf. Pomerantz, 1986).

It may be that the quality of information only has a transient influence on performance. A continued exposure to single data would properly attenuate this influence and lead to an equal performance on single data representations and information representations (cf. Kirlik, Miller & Jagacinski, 1988). For instance, the operator may learn an optimal scanning routine by which he can do the data combination at a skill-based level (cf. Rasmussen, 1986; Senders; 1966, Norton & Stark; 1972, Stark & Ellis; 1981). But there is obviously no reason to complicate the attunement to the task relevant information by spreading the data over a fragmented display, if the information can be revealed directly by visual means without getting cluttered and adversely affecting resolution, information detail, etc. (see e.g. Woods and Roth, 1988 for a discussion of the *»across-display-processing-problem«*).

The central design issue of this paper is how to combine data on graphical displays, instead of forcing the operator into a mental integration. By which visual principles can the combination be done and what kind of combinations are particulary perceptually salient ?

1.1 System Engineering and Ecological Psychology

In order to integrate the single data in a meaningful way, the ecology of the control task and the essential information must be identified prior to any attempt at representation. As an example, the information needed to land an airplane has been specified in such an ingenious way that it has become possible to represent this information with a singular arrangement of landing lights for night flights. Landing lights are certainly reduced information compared to the information in the optical array reflected from a runway in daylight, but it is *sufficient* functional information for the control task of landing. In general terms, the arrangements of landing lights enhanced the relevant goals and constraints for the control task of landing by providing the pilot with real-time, spatial and dynamic error-signals. This analogy synthesizes the central idea of ecological interface design: To make the invisible goal-relevant constraints in the interior structure of the work domain visible by direct specification, using an isomorphic, real-time mapping from the domain onto the interface (Rasmussen & Vicente (1989), Rasmussen & Vicente (1990), Vicente & Rasmussen (1990)).

Gibson (1979) uses »invariants« to refer to the properties of the optical array the perceptual systems attunes to. Hereby, he means permanent physical structures that normally remain the same across transformations. In the same sense, technical systems possess invariants given by their natural laws. An example is the thermodynamic conservation of energy in a power plant.

Normally, the attunement to task relevant invariants happens by encountering the constraints on succesful behavior. But because high technology systems do not allow for a free trial- and error-exploration of the system constraints (-except, e.g. on computer simulations), the invariants may remain unexploited as they can not be related to the specific constrains. A solution to this problem is to map the invariants of the technical process onto invariant optical structures of an interface making the task constrains explicit.

The identification of the constraints must be based on a proper analysis by system engineers. In this way, the construction of ecological inter-

Table 1. Levels of tasks and contents of a representation for power plant control

Means-Ends Levels of Description	**Typical Control Tasks in Power Plants**	**The Contents of Information Representations**
Goals, purposes, and constraints	Monitor production and safety specifications of the customers	Functional purposes and goals in terms of energy, material flow and distribution
Abstract function; flow of mass, energy, and information	Control of the flow of energy through the plant from source to electrical grid; monitor major mass and energy balances for plant protection	Mass, energy flows and balances in terms of underlying generic functions
General functions	Monitor and control individual functions such as coolant circulation, steam generation, power conversion from steam to electricity	Information on cooling, heat transfer, regulations in terms of connected pieces of equipment
Physical process of equipment and components	Adjust process parameters in order to align operational states of components and equipment to match requirements and limitations	Performance data on physical equipment in terms of information on major components components
Form, location, and configuration of equipment	Connect and disconnect components; change anatomy and configuration of equipment and installations to match requirements of physical processes and activities	Installation, maintenance information on components: take-a-part diagrams, illustrations

faces becomes a thoroughly inter-disciplinary enterprise: Good display design ensures that the optical invariants of the representation, specified by perceptual psychologists, capture the actual constraints of its ecology, specified by system engineers.

As an example of ecology related information within a technical domain, Rasmussen (1986) has specified the various levels of control tasks in a power plant and the contents of an information representation necessary for carrying out the tasks (Rasmussen & Goodstein, 1988), see Table 1.

Information from all the levels of this means-ends analysis are needed in order to control complex thermodynamic systems, especially in rare or unanticipated situations (cf. Vicente 1991). The information to be represented for the operator describes the functionality of the system as a nested set of constraints deriving from the physical laws that govern the process.

While this framework has proven to be useful for specifying the information *content and structure* in several complex work domains (Rasmussen, 1988), this article will address the general question of a suitable information *form* for revealing the constraints.

2 Perception of Computer Displays

Gibson (1979) defines a display as:

»a surface that has been shaped or processed so as to exhibit information for more than just the surface itself« (p. 42).

This definition is so general that it covers all kinds of displays from clay figures to computer interfaces. A computer display is made by the arrangement of arrays of light, representing real or imagined surfaces. Needless to say, texture, reflectance and light absorption are badly reproduced by present-day computers. But nothing indicates that this will be so forever (see e.g. Frenkel (1988) or Apodaca (1989) for a description of the achievements within advanced graphic computing and data visualizing). What distinguishes the computer interface from other displays is (1) the ease and speed by which the surfaces can be changed, and (2) the possibility for a dynamically coupling of the surface changes to the data from the events the operator is controlling, thereby keeping the perception-action loop intact. In contrast, e.g. television only allows a one-way passive perception of a fixed sequences of events.

Vicente & Rasmussen (1990) argue that the main difference between direct perception via an optic array and apprehension via a computer interface is that light as a medium is completely transparent, while the information mediated by computers will possess information specific to the computer system's own properties. Thus it becomes the primary goal to make the computer a *functionally transparent* medium to the work domain by a direct specification of the properties that are relevant for effective control (Vicente & Rasmussen, 1990). Similarly, Gibson (1979) emphasizes, that the action possibilities of the real world (i.e. »affordances«, see Warren, in press) are fundamentally integrated in the natural perceptual process:

»The perceiving of an affordance is not a process of perceiving a value-free physical object to which meaning is somehow added........: it is a process of perceiving a value-rich ecological object.« (p. 140).

Gibson (1982 pp. 289 - 291) has suggested six types of apprehension according to the degree of directness by which an affordance can be perceived:

1) Direct perception at first hand of ecological things and events.
2) More or less direct perception of the very distant and the very small by means of simple instruments (e.g. lenses) which do not significantly modify the invariants of structure in an array and therefore does not require interpretation to any great degree.
3) Indirect apprehension by means of information-converting instruments (e.g. x-rays or sound spectrographs), which display invariants.
4) Apprehension by means of measuring instruments (e.g.. meter sticks, clocks and balance), to specify the metric dimensions.
5) Indirect perception of objects, events, places or persons the information for which has been captured by a picture-maker (e.g. on a drawing).
6) The obtaining of information that has been put into words.

With an ecological approach to interface design, the structuring of single process data as goal-relevant information by means of modern information technology implies the use of a picture-maker (5) (i.e. a graphical computer) as a integrator of single metric data (4) from the automatic measures (i.e. sensors) in order to represent the invariants (3) that are relevant for the control task. Often, some of the most central invariants represented will only be situationally intelligible in an ongoing verbal confirmation with colleagues (6) in or outside the control room or the cockpit (see Segal, in press). This new conglomerate of different types of perceptual tools and human information sources makes it difficult to specify a precise degree of directness by which an operator may pick up functionally transparent information from computer displays on the basis of Gibson's distinctions. Most importantly, the degree may change as a function of practice as noted by Gibson (1982). For instance, he wrote about interpretation at the third of the levels mentioned above:

»Perhaps the interpretation of these invariants becomes more nearly direct with practice, or does in some cases, but an interpretation is nevertheless required.« (p. 290).

Gibson keeps the possibility open for a (nearly) direct perception of mediated information if the operator is presented with information specific to the task invariants and if he is well attuned to the interface. (See also Vicente and Rasmussen, 1990). Gibson's notion on »interpretation« seems to be as close as he gets to the cognitive process possibly involved in apprehension. He does recognize the need for »a complex chain of inferences« in order to utilize informations from an instrument like the Wilson cloud chamber (Gibson, 1979, p. 260), but gives no further comment on this process. Therefore, an ecological interface design approach may have to emphasize that some degree of interpretation of essential information actually can be desirable. Interpretations help keep the operator situationally aware; they provide him with symbols for knowledge based problem solving in novel situations and for communication (Rasmussen, 1986). So, the goal of ecological interface design is not to eliminate the need for interpretation, but to save the highly limited cognitive processes from being unnecessary occupied with integration of the kind of data, that the computer could just as well have integrated graphically (cf. Woods, in press).

3 The Representation of Invariants by Surface Information

The graphical design of interfaces for complex systems is a great challenge to ecological psychology, because the theory of direct perception of the natural environment in which man has developed his perceptual skills needs to be reframed in terms that can serve as guidelines for the construction of mediated information. Reframing the »ecological laws of surfaces« (Gibson 1979, pp. 23 - 24) in light of their applications on computer interfaces gives some indication of the potentials of surface invariants for the interface representation of abstract, functional system invariances. The fact that all natural substances have surfaces, and all surfaces have a layout, constitutes the fundamental possibility for surface invariants to be natural representatives for an abstract substance. The surface resistance to deformation and disintegration, depending on its viscosity and cohesion, gives a variety of representational possibilities by individual *systematic movements, deformations and disintegrations*, provided that the changes follow the laws of natural, ambient optic arrays, which specify e.g. perspective, dynamic occlusion (Gibson, 1979) and time-to-contact (Lee, 1980). As a well known example, the desk top metaphor for personal computers shows the abstract, computational function of closing a file as a gradual shrinking of its frame until it vanishes in the folder containing it.

Investigations in display perception of *shape, placement, illumination, texture, color, symbols, etc.* have been carried on within the human factors tradition for decades. The findings are far too comprehensive to be presented here, but can be found in massive lists of design guidelines and display standards (see Boff & Lincoln (1988) for an overview). They try to clarify the basic representational potentials of stimuli qualities as both basic signifiers of a substance and as dimensions through which the dynamic changes of the substance can be represented. But they tend to ignore that the perception of the persisting identity and changes of things are fundamental to the perception of individual stimuli qualities (Gibson, 1979, pp. 246 - 248). What is needed to guide the design of displays for complex dynamic systems is an approach that starts out by giving the highest priority to the visualization of persisting constraints and the invariants in changes.

In addition to supporting operator's basic perception of the constraints in the task domain, the representation must allow the possibility of forming increasingly higher compound perceptual invariances of dynamical events that »always go together« (Gibson 1979, p. 142). Within a technical domain, most of the higher order invariants are revealed in a temporal structure, e.g. heat transfer across sub-systems, mass and energy conversions and they are controlled by timed sequences of operational actions. A lot of the process invariances will exhibit some kind of often recurring cyclical patterns of events. Discovering their temporal structure will increase the feeling of familiarity with a complex system and the likelihood of an early detection of deviants from normal plant behavior. Attunement to this kind of higher-order invariant is an important part of the ongoing development of the operator's control competences, and should not suffer from a fragmented representation.

As one of the earliest examples of a display that utilizes graphical integration in order to support the formation of higher-order invariants, Coekin (1969) suggested the display of eight analogue signals as an octagon (i.e. an eight-pointed star). The idea, being similar to that of ecological interface design, is to utilize the human ability for form perception and recognition found among e.g. operators interpreting sonar displays. The scales in the octagon are arranged so that normal values of the parameters fell on the circumference of a »mean-circle« and abnormalities show up as deviations from that form. This presentation form has had several applications within technical supervisory control (Goodstein, 1981; Woods & Roth, 1988).

In a display for medical monitoring Goldwyn, Farrell, Friedman, Miller, & Siegel, (1973), have suggested a similar eleven-dimensional object. They comment, that

»The ultimate goal is to reduce a large body of complex physiologic data to an information base that is relatively small and simple so that abnormal patterns may be exposed in a manner that can be directly interpreted...« (Goldwyn et al., 1973, p.230)

Such a »direct interpretation« is possible because the polygon provides a visual integration of indications on the physiological parameters that will facilitate the formation of a compound invariant perception of »the state of health«. This is achieved by mapping persistence and changes onto preservation and disturbance of the optic array on the monitor. Thereby, it allows for a direct perception of disturbances as symmetry-breaking and focus the further interpretation on the deviating parameter(s).

Some of the most important invariant relations in process control are not at all directly visible because they don't have a natural surface; e.g. the balances of energy from the level of abstract functions in Table 1.

This problem is far from unique to process control. The lack of form of control functions, including e.g. all kinds of microchip functions constitutes the fundamental necessity for a *re-unification of form and function* on the interface (Warren, in press). Christopher Alexander (1964, p. 19) argues that »effortless contact or frictionless coexistence« between the context and the form is fundamental to all kinds of design.

Concepts and non-existent objects (i.e. imagined or abstract) can be pictured as if one was confronted with a material layout of the surfaces from real substances, e.g. of the building an architect has in mind (Gibson, 1982/1971, p. 281). It requires, that distinctive invariants of the non-existent surfaces, e.g. their imagined border lines or the difference in their individual surface reflectance, are captured in the optical structures of the picture. The natural surface of a picture is, of course, e.g. the paper or the display. It makes the very representational function evident. It is always in the midst of other non-pictorial surfaces of the environment, while being unique, as it specifies something other than what it is. Pictures are a record of invariants extracted by an observer, and they preserve what he considers worth noticing (Gibson, 1979, pp. 272 - 274).

The invisible, invariant relations in process control need a pictorial representation form that will allow the operator to apprehend the abstract system relations by the highly developed intelligence of human object and space perception. This point might seem obvious but, based on all the numerical and textual performance data found in conventional control interfaces (see e.g. Goodstein, 1981), it is not.

Some designers of new process displays do recognize the importance of graphical information on system functions and behavior. For instance, the designers of the »Steamer« interface (Hollan, Hutchins & Weitzman, 1984) wrote:

»Dynamic systems are particularly difficult to explain in language. However, relationships that are difficult to describe unambiguously in language are often easily depicted graphically. Putting a layer of interface computation between a user and a quantitative model provides a qualitative view of the underlying model. Such a qualitative graphical interface can operate as a **continuous explanation** of the behavior of the system being modeled by allowing a user to more directly apprehend the relationships that are typically described by experts« (p. 20, 1984).

4 Configural Interfaces

Interfaces that use surface geometry as their main representation of event data will be called *configural* (Flach, Rasmussen & Hansen, in press). They consist of geometrical forms which are changed according to incoming data. Here, the term »changed« is used as defined by Gibson:

> »*....change means to become different but not to be converted into something else,*..... the saying emphasizes the fact that whatever is invariant is more evident with change than it would be without change.« (1979, p. 73)

Ecological interface design gives the highest priority to the visualization of preservation and disturbance in order to capture the distinctive, functional process invariants, by mapping the goal related persistance and system changes over to the destinctive identities and changes of the form geometry. This overall intention makes the ecological interface different from mimic interfaces and metaphorical interfaces, although ecological interfaces may contain both mimic and metaphorical elements as well.

A *mimic* display is an interface where the geometry of the representation has a direct resemblance to physical features of the work domain. It is always an abstraction of the work space, as it is never as rich in detail as the actual work space (Flach, Rasmussen & Hansen, in press). The scaled diagrams of a process control plant, e.g. piping and instrumentation diagrams, will generally not preserve the exact relations of the spatial layout of the components, and the components are often displayed by icons, which only display the distinctive silhouette of e.g. a turbine or storage tank. Over the course of time, some of the objects on mimic displays have become purely conventional symbols, that bear almost no surface similarity to the actual component form, but refer to the physical process represented by the component (c.f Table 1). As an example, a valve is often depicted as two symmetrical triangles with a silhouette of a tunable regulator at the axis. Hereby, the representation moves one level up in the abstraction hierarchy from the form/location to the physical process involved. In contrast to a configural display that represents the constraints related to system functions and changes its surface form according to the functional flow state, the valve symbol always looks as if it is permanently stopping the flow, even though the regulator in the middle symbolizes the variability of the obstruction (- which is, in fact, the general function of a valve). If data on the present flow is provided, it is often in an purely numerical form.

By mapping functional invariants onto geometrical properties, the configural display gets a idiom that may look most like an abstract, cubist picture to the naive observer (see Figure 1, p. 14 for an example). This association points at some important features that configural displays have in common with abstract paintings. Marcus Hester (1977) argues that recognition and identification in modern art are concerned with very general schemata of shapes, forms, planes and lines in the picture space. The painting thereby activates a general knowledge of categories of things instead of activating a genuine identification and categorization related to the knowledge of particulars and types. In the same sense, it is the purpose of a configural interface to activate and generate general knowledge on e.g. the abstract invariants in the thermodynamic laws. The operator then gets an aid to discover the system behavior by his pattern recognition capabilities which would have been difficult to apply on a fragmented mimic representation of the system state. This is not to say that mimic representations should be avoided; indeed they are most important for the tasks at the level of physical form (see Table 1), and should therefore be represented as well, but nested within the configural form.

The use of particular *metaphors* in displays will activate knowledge of particulars and types foreign to the work domain. The purpose of e.g. the desk top metaphor is to increase the initial familiarity with actions, procedures and concepts in office information systems by letting them appear as well known objects and actions. The objects of a metaphorical definition are what Lakoff and Johnson (1980) call »natural kinds of experience« (p. 117). Hereby they mean experiences that are a product of our bodies, our interaction with the physical environment or our interaction with other people.

A specific affordance of an object is always specified by the object's effectivity in an action context. A hammer e.g., normally affords amplifying the blow, but it can also be used as a hook, if one wants to reach out for a box of nails. When a particular object is used as a metaphor for computerized »tools«, it does not retain the functional complexity and multiple affordances it can have in natural experiences. A metaphorical representation of a delete function by a rubber icon might be used to erase a line, but - much to the user's surprise - not to delete a filename.

So, ironically, the force of the pictorial metaphor - that it imports particular understandings from natural experiences - is also its weakness: These understandings smuggle in the multiplicity of effective actions the object makes possible in natural experiences. In complex, technical domains, where the possible system states can not be foreseen, novel reasoning using imprecise metaphorical symbols can be catastrophic. Therefore, it does not seem like a good idea to reframe control tasks into e.g computer game metaphors, as proposed by Carroll & Thomas (1980).

Configural displays attempt to map the functional structure from the target domain onto the geometry of abstract forms. In a sense, their metaphorical domain is simply geometry. (Flach, Rasmussen & Hansen, in press). While particular, pictorial metaphors associate to a foreign domain object, the abstract space and object metaphors in configural displays are supposed to be almost neutral in their generality. It is assumed that their lack of specific connotations makes a direct mapping to the work domain events possible, as they do not demand considerations about the interfering objects in the mapping process itself. Metaphorical objects have a one-to-many mapping from their representation to natural experiences, but only one (or a few) correct mappings back to the target domain. So the interpretation of inherently imprecise particular metaphors may force the operator to consider their intended meaning in order to map them back from the foreign domain to the plant situation. Even if the operator gains a high familiarity with the imprecise nature of particular metaphors, he may still have to suppress some of his obvious, but »false« associations. In short: the less the load from foreign meaning, the higher is the likelihood of a direct mapping. A configural representation that does not look at all familiar is most likely to be associated with nothing but the real-world events that makes it change.

It is important to recognize that, although not intended, abstract configural interfaces may activate intuitive idiosyncratic interpretations because they rely on human perception skills that have developed in the natural environment. Their relation to natural experiences may first become clear when a configural interface representation violates the laws of the four dimensional Newtonian time-space world. (cf. Winograd & Flores (1986) notion of »breakdowns« and Alexander's (1964) notion of »misfits«). For instance, a display that ends up representing mass increase by a shrinking form or a particular temperature increase by form moving downwards will most likely be counter-intuitive. Unfortunately, the precise form of these common, governing intuitions is not known in detail. Lakoff and Johnson (1980) point at some important features of natural intelligence and some research has been concerned with the naive physical interpretations of the abstract functionality of (simple) mechanical systems (McCloskey, 1983, Kleer & Brown, 1983, diSessa, 1983, Gentner & Gentner, 1983). But there is no general »basic cognitive semantics« available that can be used directly as a design guideline for the selection of geometrical metaphors. Moreover, movements of representations of e.g. chemical reactions will not always follow the laws of material kinematics, but may follow non-linear and higher order laws. So, at some point, a representation may have to make exceptions from the Newtonian laws anyway. In fact, as these exceptions presumably are difficult to grasp intuitively, they should be clearly emphasized in the interface, making it educational as well as perceptually salient.

A partial solution to these problems, suggested in the next section, is to choose a highly restricted set of simple geometrical principles as a graphical syntax that creates a coherent time-space world following its own underlying geometrical relations. By recurring use of a few principles, it is intended to create a visual language that only uses graphical features which (-in principle) can be tested for their individual perceptual salience and connotations. Even so, it is not believed that the visual complexity of large scale system representations and the specific connotations of operators in an actual work domain can be foreseen. This makes the interface development intimately linked to the cognitive task analysis and points at the inevitable need for user feedback in an iterating system development process (see e.g. Gould & Lewis, 1985).

5 The Nesting of Information

The structuring principles for display surface invariants must facilitate the pick-up of information at the individual levels of control (see Table 1), without violating the possibility for decomposition and aggregating of information between the levels. According to Gibson (1979), direct perception of the natural environment possesses the quality of utilizing a lot of nested information that forms a kind of hierarchy without categorical bounds. This is exactly the feature that should be achieved when multi-level information is displayed simultaneously in ecological interfaces, cf. Flach, (1988; 1990) and Gaver, (1991). Alexander (1964) too, regards nesting as a general design aim:

»We ought always really to design with a number of nested, overlapped form-context boundaries in mind« (1964, p. 18).

In the following, some general, graphical heuristics for the nesting of information by display geometries will be suggested. The principles are inspired from well-known illustration principles (Se e.g. Tufte (1983,1990) or Cleveland (1985)) and modified to capture the specific values within process control (cf. Table 1).

1) *Goals as figural goodness:* »Goodness« is a very vague term from Gestallt psychology (Zusne, 1970), but there might not be a better word for the aesthetic quality it refers to. Here it implies that, when the system is in a goal state, the display representation should show as much linearity, alignment, symmetry and/or balance as possible within the given format. On the other hand, deviations from the goal state should be clearly visible as e.g. non-linearity or symmetry-breaking. Examples: landing lights and the Coekin star.

2) *Constraints as containers:* The constraints identified in the task analysis map onto permanent forms of the background. The constraints may range from overall goals (e.g. productions goals) to the individual component capacity. Example: a storage tank symbol with an area analog to its volume capacity.

3) *Dynamics as figural changes:* On top of this background, the dynamics of the process are mapped to geomertical figures that change according to incoming data. Through the operator's control actions, the dynamic figures are to be kept within the borders of the constraints. Example: mass flow represented as a changing area in e.g. a storage tank.

4) *Functional relations as connections:* Contact in the form of lines, intersections or coincideness are used to indicate a functional connection. Example: piping diagrams indicating possible mass and energy transportation.

5) *Pictorial symbols as component representations:* The actual physical appearance and configuration of the equipment may be represented by a detailed, mimic form. Example: valve-symbols.

6) *Alpha-numerical signs as additional support:* The nesting of text and numbers within the configural format can increase the data resolution and provide means for communication and symbol-based reasoning in novel situations. Example: numerical information on e.g. a pump performance, maintenance information on components.

7) *Time as perspective:* The gradient of density (Gibson, 1950) can be used to represent temporal changes by mapping time onto depth. Example: the time tunnels (Hansen, 1989) described in Section 7.2 of this article.

All real world design has its trade-offs according to Alexander (1964). So will interface design based on the seven principles suggested above. It is not the individual suggestions (except, maybe, 7)) that are really new. It is the ambitious aim of:

Integrating 1) and 3), and...
putting them on top of 2), and...
letting 4) decide the placement of 2) without spoiling the integration of 1) and 3) and...
making a natural relation/transition between 2) and 5) and...
show 3) by 7) with
6) added when needed.

This ideal might be impossible to achieve for at given set of invariants and constraints from a control domain. But in at least one complex domain it has been partly possible, namely Lindsay & Staffons (1988) interface for a nuclear power plant, see Vicente & Rasmussen (1990) for a detailed description. The next section illustrates the author's attempt to apply the principles.

6 An Example on a Configural Display

Figure 1 is a sketch of a possible representation of the temperature constraints in a conventional power plant domain that will reveal the invariants in the conservation of energy. It is inspired by an interface developed by Lindsay and Staffon (1988) (see Rasmussen & Vicente (1990) for a detailed description) where the incoming temperature data, following principle 3, forms a Rankine thermodynamic cycle (the closure figure with thick lines), originally suggested by Beltracchi (1987) as the structuring principle for a Breeder nuclear reactor display. The Rankine cycle shows the thermodynamic relationship between entropy (x axis) and temperature (y axis). It is composed of four general process functions: 1) heat addition to the water, which results in a phase change from liquid to steam, 2) an reversible expansion of the steam, which does work upon a turbine, 3) an reversible heat-rejection process of condensation, which results in a phase change back to water, and 4) a compression of the water by means of pump work (Beltracchi, 1987).

The thermodynamic cycle is contained within the related constraints (principle 2) of the subsystems that generates it and within a graphical representation of the basic thermodynamic relationship between temperature and entropy for water (the sugar top-like curve). At the left side, the thick line represents water, within the curve a two-phase mixture of water and steam, and on the right side dry steam. Engineering analysis of the thermodynamic laws have clarified, that it is critical that the burning and pressure are regulated so that the water boils within the curve. If this constraint is violated, the boiler may be filled with steam or filled with water. Both cases will make its control unsafe and may violate either the temperature constraints or the pressure constraints, respectively. Saturated steam and saturated water in the boiler are indicative of normal operation whereas the presence of superheated steam is indicative of abnormal operation (Beltracchi, 1987). Even though operators do not use entropy as a critical variable - actually, the entropy dimension gets dropped in the display implementation (cf. Beltracchi (1987)), - the advantage of the temperature-entropy diagram for display is that constant pressure lines, which is a critical operational goal indicating a normal boiling process, becomes horizontal in the two-phase region in this presentation format. Horizontal lines are an example of figural »goodness« (principle 1) that maps onto a goal state, and the use of the entropy figure is an example of how the constrains identified in analysis of the abstract process functions are made available to the people controlling it (principle 2).

Another advantage of this format is that the area of the Rankine cycle represents the net energy of the system. The area from temperature point 21 to 303 and down to the base line in the condenser shows the heat energy of the liquid water, the area within the curve and down to the base line shows the energy added by boiling and the area under the section from the right side of the curve to the top point (576 degrees Celsius) the energy added in the superheater. The distance from the top point to the condenser point (46 degrees Celsius) represents the work being carried out by the turbines (cf. Knark, 1982).

The various physical sub-systems involved in the energy production is nested as boxes around the Rankine cycle. Besides their being a reference to the individual sub-systems (pre-heater, boiler, superheater, turbines and condenser) the size of the static boxes indicates the upper and lower temperature constraints of the sub-systems. Moving down to the level of physical form (cf. Table 1) could then e.g. be done by choosing one of the boxes for various detailed pictorial component information (blue-prints, CAD-drawings, video pictures, etc.) (principle 5).

In present control rooms for conventional power plants, the most direct and fast indication of the burning process itself is provided by bar graphs whose heights are analogous to the luminescense of the flames. This crucial information is nested inside the Rankine cycle below the boiler temperature indication and on top of the coal-mill representation in order to resemble the

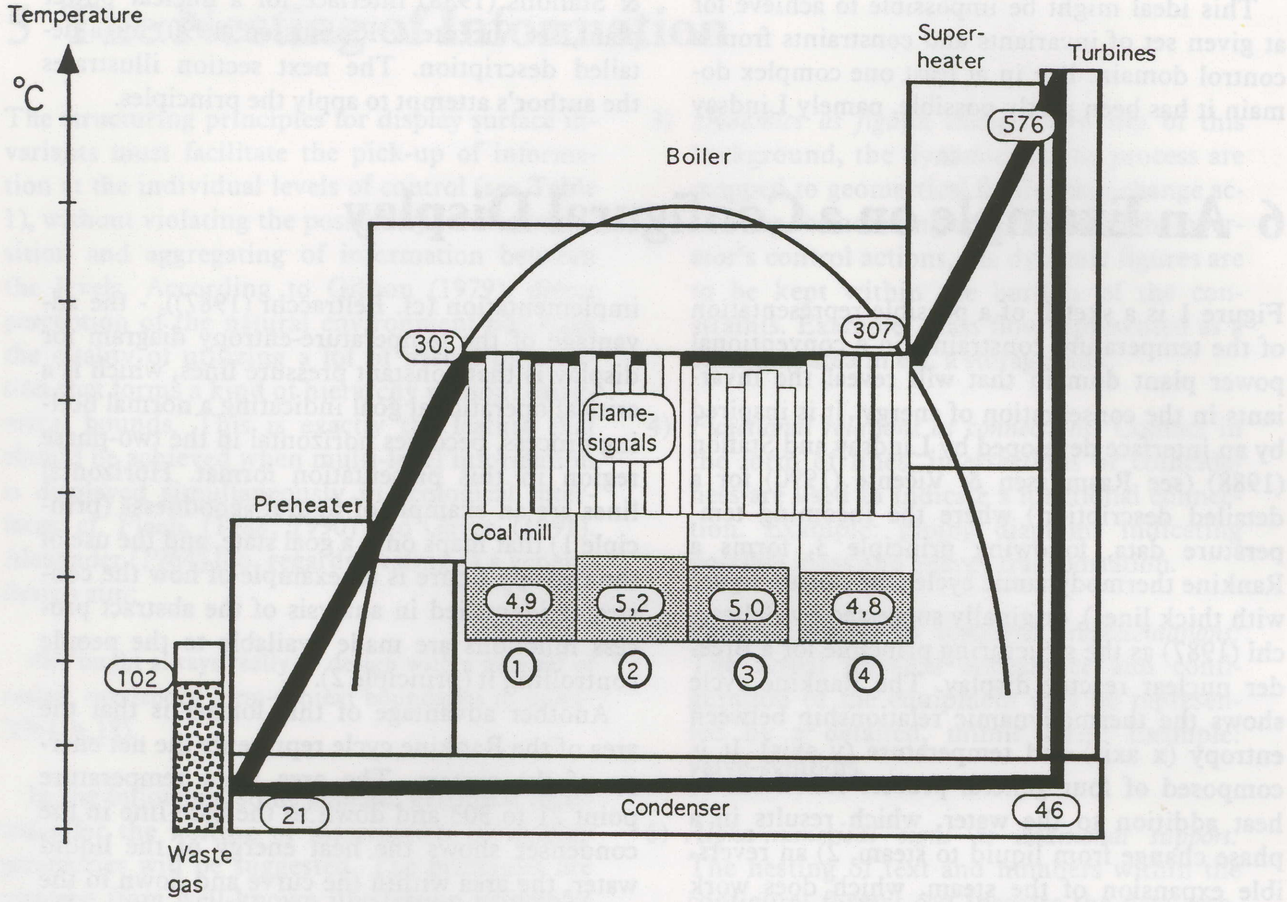

Figure 1. A sketch of a configural display for control of conventional powerplants. See text for explanations.

elemental relationship between fuel feeding, burning and energy generation. If the flame signals from the burners at one coal-mill become weak as shown at coal-mill 3, the most likely cause, namely a lack of coal or an unbalance in the air-coal-masses can be checked at the coal-mill box. Inside this box, the actual coal load is shown as a gray surface and if the invariant relation between coal and air is not maintained, the area will either fail to meet the borders, indicating that too much air is blown in (as it is the case on coal-mill 3 in fig. 1) or it will exceed the border of the coal mill box, indicating a lack of air for the amount of coal fed (principle 2 and 3).

The sketch is only meant to illustrate some possibilities for the nesting of constraints and invariance representation in configural interfaces and is not recommended for any implementation in its present, rudimentary form. The crucial information on the actual energy-production is not included. In addition, it does not directly capture the water and steam masses circulated, although this might be done by e.g. making the thickness of the figure line analog to the masses.

7 General Discussion of the Nesting Principles

This section will provide further theoretical and empirical arguments as supporting evidence for the nesting principles suggested in Section 5, and discuss some practical aspects of their application.

7.1 Configural Displays of Abstract Data Relations

Lakoff & Johnson (1980) recognized the overall principle of transforming abstract relations into figures with properties like spatial orientation, entity, substance and containment as an important part of the pre-linguistic natural intelligence which governs the formation of metaphorical transformations in language:

»Spatial orientations like up-down, front back, on-off, center-periphery, and near-far provide an extraordinarily rich basis for understanding concepts in orientational terms...... Our experience of physical objects and substances provides a further basis for understanding - one that goes beyond mere orientation. Understanding our experiences in terms of objects and substances allows us to pick out parts of our experience and treat them as discreet entities or substances of a uniform kind. Once we can identify our experiences as entities or substances, we can refer to them, categorize them, group them, and quantify them - and, by this means, reason about them.« (1980, p. 25)

The suggested principles of figurality and display of functional relations as contact, seems to have a primacy in the ontogenesis of perception. Reviewing investigations in infant perception, Spelke (1990) summarize the general findings:

»Infants divide perceptual arrays into units that move as connected wholes, that move separately from one another, that tend to maintain their size and shape over motion, and that tend to act upon each other only on contact.« (p. 29).

Applying these principles as visual means by which system states are experienced should insure that they have a natural relation to human cognition and can be percieved with well established perceptual skills.

Some of the graphical means like size, closure and symmetry were recognized by the early gestalt theory and used as explanations of e.g. the figure-ground phenomena (Zusne (1970)). As they mainly were related to perception of static 2-dimentional figures, the importance of pattern changes during events have not been discussed in greater details within this tradition. In general, the gestalt tradition has identified some important principles for perceptual integration and illusions but tends to ignore the close link between form perception and invariants in change. One of the main principles of ecological interface design is to preserve and utilize this link by means of direct visual feedback on all actions (Rasmussen and Vicente, 1989).

According to Pomerantz's (1986) widespread definition, it is some specifiable emergent feature, dependent on the identity and arrangement of the parts (- but not identifiable with any single part), that »pops out« and configures parts into wholes. Closure and symmetry are examples of emergent features. In addition to this phenomenological definition of emergent features, he suggests that figures with emergent features will be perceived faster in divided attention tasks, where all parts have to be taken into account, and perceived slower in selective attention tasks, where responses are contingent on some individual parts, compared to displays without emergent features.

Experiments have shown configural displays to be more rapidly perceived than separable displays in data integration tasks. For instance, Carswell & Wickens (1984) found that a triangular display was approximately 800 ms faster perceived than three separate bar graphs. Recently, Wickens & Andre (1990) compared an area object display with three bar graphs and obtained a reaction time (RT) superiority of the same magnitude.

Sanderson, Flach, Buttigieg, & Casey (1989) demonstrated that it is not the objectness per se which causes faster RT for these kinds of displays, but their exploration of emergent features. They found that three bar graphs, traditionally viewed as a typical example of a separated display, with an ascending or descending linearity as an emergent feature in the target situations, was perceived faster in a data integration task than a triangular display. This experiment is particularly interesting because the ascending or descending linearity was not actually shown, but mentally imposed by the subjects themselves. This means that emergent features may arise from invariant higher-order cues which map onto a required response and that the discovery of these cues becomes an important factor for the development of efficient visual scanning strategies.

Buttigieg (1989) used the same type of interface and found that the subjects were actually able to verbalize the emergent features exploited as cues. In Rasmussen's (1986) terms, the utilization of an emergent feature may then be supported by a conscious rule, specifying a sign about the target situation, which keeps the skill based signal detection on the configural displays focussed and »on track« during practice. (See Hansen, Løvborg & Rasmussen (1991) for a similar example from the development of visual skills on computer games.) This interaction between cognitive and perceptual processes has important implications for the construction of configural interfaces: Pomerantz (1986, p. 13) warns that the emergent features associated with grouping and configuration result from idiosyncratic and unpredictable interactions of parts and, as a result, they can produce unusual effects that can easily be misinterpreted. Although this is an important risk to consider, the positive aspect of unpredictable effects should also be emphasized: Some of the effects may actually be highly informative with regard to the system state and their sign properties makes a communication between collaborating operators possible as an exchange of procedural knowledge (i.e. - »what to look out for«) during cue learning.

Currently there seems to be no a priori, formal way to »speed up« the perception of complex interfaces as their emergent features are partly out of control, determined as they are by both the representation, the task objective and the observer. But the fact, that emergent features on a given interface phenomenologically »pop out« and can be verbalized by the users makes it possible to evaluate if they are at all available and if they match the system goals.

A low RT for integration tasks may be an indication of the availability of an emergent feature, but it is certainly not a sufficient criteria for the choice of a process control interface format. Possible trade-offs between RT, hit-rate and false alarms must be considered carefully for any interface format.

In real-life situations, the cost of false alarms may be very high if there is no possibility for reversible actions. It is most likely that the cost of misjudgments will have an overall impact on the operator's decision strategies, as pointed out by Rasmussen (1986). When the choice of strategies is not »blocked out« by a simple task instruction, as it most often is in perceptual experiments, different task dependent strategies may change the way and speed by which operators react to available information. For instance, as noted by Buttigieg (1989), subjects in this kind of experiments may not be as conservative as operators in the real world would be.

So, even though configural displays experimentally have shown a higher hit-rate than separable data displays (see e.g. Goldsmith & Schvanefeldt, 1984), this may be restricted to situations with no cost of false alarms, as the hit-rate naturally will increase if the operator is allowed to »take chances«. Configural displays may increase the »chance« (i.e. risk) of overlooking counter evidence while separable data displays force the operator to take the individual status of the parameters into account before he can respond.

Only a task analysis will be able to tell the actual importance of RT, hits and the cost of false alarms on a given plant. On basis of this analysis, perceptual experiments with different formats can be conducted, e.g. by the use of an interactive computer simulation of the plant invariants, and the results evaluated against the specified criteria.

7.2 Graphical Remembering: Making the Past Present in Order to See the Future

While most of the suggested principles can be seen in other types of interfaces, the idea of displaying temporal changes by the use of perspective is believed to be novel (Hansen, 1989). A representation of the fluctuation of plant data over time is needed for the supervision of trends, gradients of changes, process response time and other time-dependent events (Boël & Daniellou, 1984; Leplat & Rocher, 1984). One of the reasons for this is the considerable time lag on most basic indications due to the inertia of physical systems. For instance, work observations in a modern control room for conventional power plants by Bærentsen, Kvorning & Skov (1989) revealed that it can take almost five minutes from a reduction of the coal load until a decrease in the megawatt production results. During this period, the operator has to remember the former flow status and compare it with the the current values in order to extrapolate the system state in time, e.g. to estimate whether he will reach the specified production goal. Everything that has to be remembered may be forgotten, especially in situations with a high mental workload.

The information support for extrapolations is often provided by strip charts located out of view from the operator's central control position. As an example, during a routine load reduction examinated, the operator had to move four times from his control monitors to the plotters at the back control board within half an hour of intensive control and adjustment. He explained why:

».....at the back control board it is possible to see the development .....here *(at the central control monitor)* one can only see where it is *(right now.)*.....« (Bærentsen, Kvorning & Skov, 1989a, p. 3). (Explanations in italics added by the author).

This example points at the importance of having temporal information present in an easily assessable form. Gibson (1966) emphasize that time is not a perceptual dimension, but a construction a posterior, based on the dynamic structure of the perceptual field. According to De Keyser (1991), several representational metaphors have been applied to support this construction. As one example, time can be expressed as *movements over a distance.* De Keyser (1991) argues that certain events like incidents, testing, unusual productions, organizational changes or turbulence in the process break up the established regulation strategies, including the temporal ones. In e.g. plant tests, the usual temporal references of the operator no longer exist, and they must resort to calculations of duration, which they apparently do not always master, as indicated by the higher accident rate in these situations. Having identified this need for temporal information, De Keyser (1991) describes the cyclic patterns within the medical field and continuous process control. However, she does not discuss the possibilities for an interface design approach to the problems identified.

An interface addressing this problem will have to integrate, in one single representation format, 1) the *»objective clock time«*, which is the semantic-free, discrete and totally ordered invariant used for the construction of the control system itself and the unchangeable constraint of all (macro-) physics, 2) the *evolution of the variables* of the process, for instance temperature, and 3) a *configural form* with a symbolic reference to the functions being represented. As individual design goals, the clock time can be represented by a watch. The evolution can e.g. be traced by decaying shades of former indicator positions shown as an afterglow, and the system functions can e.g. be represented by the 2 dimensional figures of theoretical physical explanations, found in text books and instruction manuals.

To integrate these representations, it is suggested to start out with a 2-dimensional figure of the invariants, e.g. comprising the Rankine cycle, as it captures the constraints of the physical laws which can not be changed. Then show the changes of parameters as changing forms within these constraints. Information to trace the development in the form of afterglows does not show the objective clock time through which the development takes place, since no monotonous, one-directional process movements can be assumed. Neither do displays of evolutions by fast (video-) playback of the changes, as this breaks up the natural temporal structure by which the invariants normally are seen in the changing interface geometry. Therefore, some time indication on the display (e.g. a clock) is required in order to reconstruct the temporal dimension mentally.

By giving time a dimension for itself, it can be specified directly. As a matter of fact, 75 % of all public statistical information do reserve one dimension for time, according to Tufte (1983):

»With one dimension marching along to the regular rhythm of seconds, minutes, hours, days, weeks, months, years, centuries, or millennia, the natural ordering of the time scale gives this design a strength and efficiency of interpretation found in no other graphic arrangement.« (p. 28).

But often the two dimensions will already be occupied by other physical entities; the Rankine cycle, for instance, needs them for temperature and entropy. This leaves no other alternative than applying the third dimension. Hereby, the basic format can be preserved; the evolutions of the form reflecting the abstract physical performance can be traced by comparisons between former or proceeding figures while the invariant structure of the perspective shows the invariant, objective time.

If objective time was not a basic constraint and thus alredy embedded in a lot of the control sys-

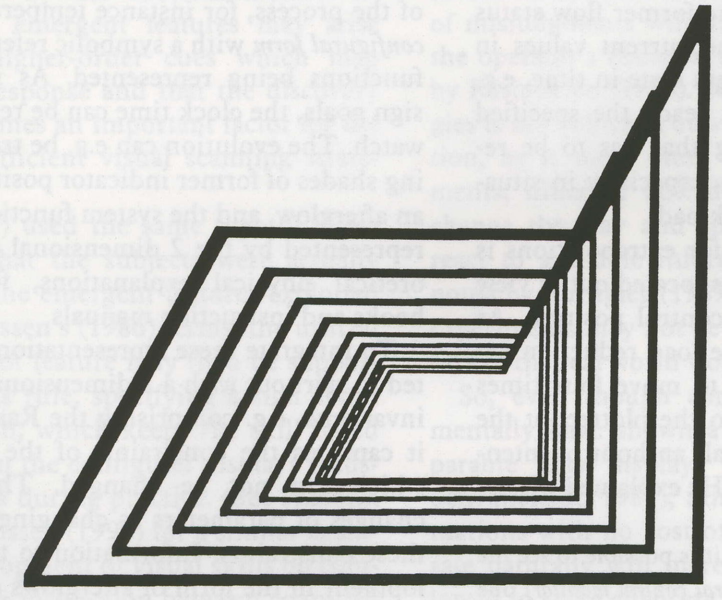

Figure 2. Former data measurements of the temperatures in the power plant can be represented inside a dynamic configural form, by a monotonious mapping of constant time intervals between updates onto the gradient of density which specifies the gradually, perspective shrinking of surfaces.

tems' regulation algorithms and alarms, it might have been omitted in the display format. If operators had perfect memory structured by an accurate biological watch, it might also have been left out. As this is obviously not the case, the time dimension needs a direct specification.

Applying the seventh graphical principle from the list of nesting possibilities in Section 5, Figure 2 shows what the temperature cycle from Figure 1 would look like in a stable plant condition, if time is mapped onto depth, using movements over a distance as the abstract geometrical metaphor. Note that constant time intervals between each update are a prerequisite for the direct specification of the time span displayed.

Figure 2 shows the rankine cycle over time from a static, central perspective. From just this one perspective changes in temperature may be very difficult to pick up, as the graduate shrinking may mask and occlude some of the dynamic figural changes. In Section 8 this problem will be addressed again, by arguing that multiple perspectives of the same figure have obvious perceptual benefits, and can be achieved with the new technique emerging within virtual media environments.

The use of depth to represent time have been termed »Time Tunnels« (Hansen, 1989). He has suggested a modification of the Lindsay & Staffon (1988) interface, which shows the information of four incoming data as a quadrangle in front (see Figure 3), that pushes nine older sets one step »backwards« at each updating, using perspective to map time over to depths. This gives the sketch of a tunnel, with the impression somehow like looking backwards from the last car of a roller coaster while the props pass by. As the process moves further in time, the figure shrinks into the distance and new measurements appears in the foreground. Symmetry or asymmetry in the pattern over its depth reveals invariances and changes in the relationship among the four variables.

The intention is to induce the formation of a higher-order invariant perception of the process state (e.g. »being in a steady state« or a »unstable state«) and the process history (e.g. »increasing«), by the use of the natural perceptual skills for perceiving the invariants in perspective and changes in patterns.

A recent experiment (Hansen, in press) has compared the perception of trends (i.e. simultaneous decreases on eight parameters) on the time tunnel display with other separated and integrated formats. Three sets of data with different rates of change and bandwidth were used. The utilization of the third dimension in the time tunnels was found to increase the number of cor-

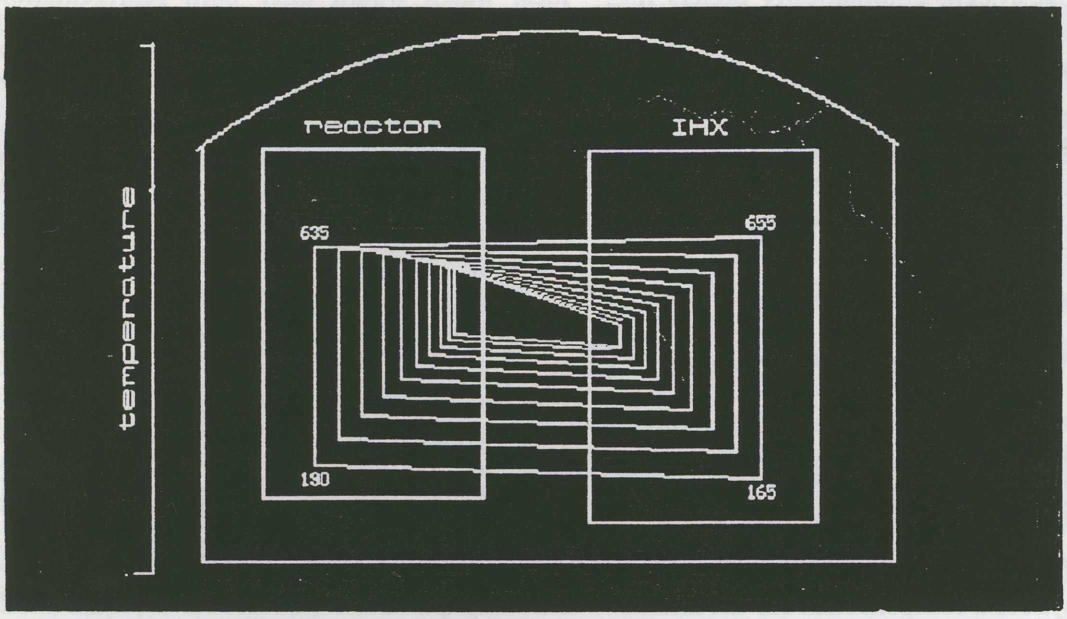

Figure 3. A time tunnel depicting the increase of temperatures in the intermediate heat exchange of the primary coolant cycle from Lindsay & Staffons (1988) display format. Four temperature measurements from the water going out of the reactor core (upper left corner), into the intermediate heat exchange (upper right corner), out of the exchange (lower right corner) and back to the core (lower left corner) naturally expands a quadrangle. Older measurements are shown inside this box, shrinking according to the gradient of density in natural perspective. It integrates information on the evolution of parameters over time, the objective clock time and a symbolic representation of the function. This information is supposed to be accessible at »one glance« due to its exploitation of a natural invariant in the optical structures.

rect responses in conditions with noisy data where changes have to be extracted from nonspecific, dysfunctional information. The experiment also revealed a general superiority of integral formats compared to separable formats and a lower reaction time when numerical information was nested inside the graphical information (see the next section).

The time tunnel display violates the invariant laws of ecological optics in three important ways: First of all, there is no dynamic occlusion of what would have been hidden frames, as there are no surfaces between the frames. Secondly, the lack of surfaces excludes the information in texture density, and the frame lines have the same thickness down through the tunnel sketch. Third, the significance of changing perspective with (head)-locomotion is ignored, as the arrested perspective in the time tunnel display only specifies what Gibson (1979) calls an *artificial perspective*. An artificial perspective, as it is found on pictures, requires that the representation be viewed with one eye at a unique station point and this was not the case in the experiment. The limited numbers of frames used, namely ten, may also cause some perceptual problems. Gibson, Purdy & Lawrence (1955) presented subjects for an optical tunnel composed by alternating white and black plastic sheets with an increasing density of the contrast from the periphery to the center. They found that two-thirds of the objects saw a tunnel when nineteen contrasts was displayed, but only one-third did so if the contrast was reduced to nine. So, it might well be that a more direct perception of the time tunnels can be achieved if the numbers of frames is increased. Even with these violations, most subjects actually express a phenomenological percept of »moving through a tunnel« when they are presented to the time tunnel display. Similarly, Johansson, Von Hofsten, & Jansson (1980) found a perceptual tendency toward abstract projective invariances so strong, that a highly complex and »unnatural« motion in three dimensions was preferred to a simple two dimensional track trace by two moving spots. They provide experimental evidence, that the visual system automatically prefers invariants of figure size, obtained by inferring motion in three-dimensional space. This preference is supposed to be in effect when perceiving the time tunnels as well, and to be strong enough to overrule the violations.

The violations and shortcuts were caused by the computational and display limitations of a standard personal computer. In the near future most of these limitations will disappear. Section 8 of this article will discuss the representational potentials of the new visualization techniques.

7.3 The Importance of Digital Information

One could claim that alpha-numerical signs and symbols always are a compensation for the lack of direct specification of the affordances in the visual form. This point has been made within architecture, c.f Warren, in press, and it applies to process interfaces as well. But alpha-numerical signs do have some important qualities as a mean for rule-based behavior (Rasmussen, 1986); they can be communicated verbally to (remote) collaborating human agents and they can hold a higher individual data resolution than pictorial representations (Hansen, in press). So, textual and digital signs are not to be totally removed from ecological interfaces but used as additional information when the task analysis points to the importance of their use.

Several experiments have pointed at the lack of precision in the judgments based on graphs. Brunswik's (1956) classical investigation into the differences between perception and thinking involved problem solving on the basis of two different representations of the same task, each inducing one of the two processes. The graphical representation lead to large amount of responses close to the right answers with a low variability, while the analytical representation gave more precise correct answers, but with a much higher standard deviation, as a result of several extreme misjudgments.

van Nes (1972) compared mental subtractions on analog and digital watch displays and found that in order to determine a relatively small time difference quickly and precisely from the displays, the representation should preferably be digital. If only a rough estimation (like a full or half hour) is needed, subtraction is believed to be easier with an analog watch. He suggests that the ideal watch would offer both representations, which is actually common on several types nowadays.

Cleveland (1985) has discussed the precision of judgements on different graphical formats and suggested a priority list of graphical means like position, length, angle, area etc. on basis of empirical investigations. But it is difficult to apply this kind of low level evaluation to more complex interface design where several of these means will be applied and interact in one display solution, cf. Pomerantz (1986) warning on the unpredictable nature of emergent features. What is the interaction-effect on the precision of the (redundant) information provided by e.g. both the angle **and** the area of a simple pie-chart diagram or the angle **and** the slope of a line in a curve display? It remains an open question as to whether the interaction effects alone can achieve a requested degree of high precision. There is evidence of a definite limitation on the resolution of configural displays. For instance Veniar (1948) found that horizontal or vertical distortion of a square shape will not be perceived when the distortion is less than 1.4 % of the original length. If the control task requires information precision below this threshold and if an upscaling of the configural displays will spoil the area dispositions of the overall interface, adding digital information seems to be a natural way to overcome the shortcoming.

The exclusive use of one of the two information types might not be satisfying from a safety point of view. In some cases, e.g. when the operator needs to report the specific state of a process to outsiders, it is important to provide him with information that can be verbally coded. In unanticipated situations, (i.e. rare events) the precision might eventually turn out to be crucial for control actions based on knowledge based reasoning (Rasmussen (1986)). For instance, when a small leak has been correctly diagnosed, the operator might want to calculate its exact amount in order to compensate precisely for the loss.

Most of the real life control systems the author has seen do in fact have a mixture of mimic, graphical (i.e. curves or bar graphs) and digital information. So, human factor experiments in touch with realities should not treat the discussion on graphical versus analytical (e.g. numerical) interfaces as an »either/or issue« but instead consider ways to improve their integration. As it is the numerical data that drives the graphical display, they are computationally accessed anyway and may be displayed in addition to the graphic at a very low cost in terms of occupied space. It is commonly assumed that when distributed in the spatial, dynamical state space of the display (see Figure 1 on page 14), the digits association to the actual physics will be strengthened. In contrast, it will be much more difficult to add graphical figures to a fundamentally numerical display layout, due to the constraints imposed by the alpha-numerical tradition of serial- or table-representation formats.

The previous discussion can be summarized as a threshold scaling problem: How much difference will »make a difference« in the actual domain and should therefore be made perceivable? Is it important to hold a very high degree of precision obtained by analytical representations or will close estimations induced by graphical representations be sufficient? This question too, emphasizes the close coupling between graphical interface design and task analysis.

While it has been possible to perform cognitive task analysis on complex work domains (Rasmussen, 1986) and important efforts are being carried out to generalize the experiences from this work in a taxonomy for cognitive task analysis (Rasmussen & Pejtersen, in press), there is still a need for basic perceptual evaluations of interfaces and for developments of new display forms. The task analysis specifies the information content, while human factors research should specify and justify the most efficient form to represent this content by, making it compatible with the human sensory mechanisms. The last section of this paper discusses the the future possibilities of utilizing projective geometry as a new display form which may allow visual displays to become more complex without getting cluttered.

8 Outlook for the Future: From Artificial to Natural Display Perspectives

Driving a car through the rush hour is an example of how quickly and smoothly people can pick up a large amount of information in the structure of light under shifting operational conditions. Jens Rasmussen (personal communication) has described the control task of a high technology system operator as driving a car with a black, non-transparent front wind shield on the basis of information communicated from passengers looking through the back windows. Although this sounds like a very unsafe control condition, anecdotes tell that Gibson scared his car passengers by demonstrating how the information in the optical flowfield through the side windows specified the information necessary for driving. When the constraints of the road are straightforward and no unanticipated obstacles occurs, the history in the flowfield provides sufficient information about the future safe direction. What the driver needs is visual information not so much about his current position on the road but about his potential future course were he to maintain the current steering angle, as Lee (1980, pp. 176 - 177) formulates it. An ecological interface should provide this kind of information by making future states visible within the constraints of the physical laws that govern the process, using the optical invariants in motion perception. Examples of such invariants are the geometry of transformations, preserving the »point-to-point and line-to-line correspondence« (Gibson, 1950, p. 153) during the change of viewing positions and the invariant of radial expansion of a portion of the visual field, giving rise to the experience of an obstacle »looming up« from a particular direction (Gibson, 1979, Lee, 1980).

Gibson (1979) argued that the invariant structure of the ambient array of light separates off best when the frozen perspective structure begins to flow with every displacement of the point of observation. This feature was not achieved with the time tunnel display due to computational limitations, regardless of the rigid movement »backwards« - nor is it achieved in any other present day control systems the author is aware of. But displays with a flow of optical structures slaved by head movements are now emerging. Fisher (1982); described a system with an interactive, lifesize, stereoscopic window into a displayed representation. The user's movements are tracked by a small magnetic device worn on his head and the data on his actual position is used to change the viewpoint of the represented data. The screen constantly shifts between two recordings of the same scene, only differing in an offset at 6.5 cm along the x axis. When this display is viewed with special glasses which block out one eye at a time, synchronised with the image shifts on the screen, the resulting image provides binocular parallax information. Hereby binocular disparation, motion parallax and motion perspective are achieved. Later versions of this system (see e.g. Fisher, McGreevy, Humphries, & Robinett, 1986)) have built two screens into a helmet-mounted pair of goggles, one for each eye. It is operated by position, voice and gesture input. The gestures are recorded throug a data glove, which senses the position of the hand and the bending of the fingers. Now the user can virtually explore a 360-degree synthesized or remotely sensed environment and interact with its components. Fisher et al. (1986) identifies large-scale integrated information systems as one major application area for this type of system, arguing that efficient supervision of automated systems will depend on highly graphic, multi-dimensional status representations of the numerous subsystems, especially in case of system degradation or conflicts in resource allocation.

User experiences with these kind of systems are now reported. Pausch (1991) has observed that the quality of the graphics is not as important as the interaction latency. Users can tolerate low display resolution if the display is driven by head movements, but they will notice if the time lag is more than 200 milliseconds. Big lags may actually induce motion sickness, according to Foley, van Dam, Feiner, & Hughes (1990) (see also Hettinger, Kennedy & Rico, in press). Binocular separation is not that essential (Pausch, 1991) as satisfying monocular interactions with the systems are most often found possible. It is recommended to show an artificial ground plane for reference while orienting in the seven degrees of freedom (three for body position, three for head movements and one for zoom) and to show the constraints of the physical room in which the equipment is worn. This information is combined in a »vehicle«- metaphor which gives the user the impression of standing onboard a flat, stage-like object (Pausch, 1991). Some of these experiences call for a theoretical explanation from ecological psychology, e.g. on the importance of a ground plane to scale objects according to eyeheight. But in the context of this paper, it is the new possibilities of achieving natural perspectives on ecological control displays that is the central issue (see Smets et al. in press or Mestre, Peruch, Savoyant, & Pailhous, in press for an ecological approach to virtual media environments.

The perception of configural displays with perspective may be greatly improved if the operator is allowed to inspect the figures from different points of observation (Smets et al., in press). The areas occluded from the artificial perspective could be revealed by moving sideways, by lowering, by raising or by tilting the head. Familiarity with the process event-invariants would be based on the distinctive, formless and timeless object invariants in the optical structures of the representation. The notion of the formless-ness and timeless-ness emphasizes that the invariants resemble a whole sequence of perspectives picked up by many views: It is the presence of the invariants and not a simple pattern recognition of the corresponding points of light from a particular perspective that makes a good representation (Gibson, 1982/1971).

Returning to the problem raised in Section 7.2 with the possible masking and occlusion of dynamic form changes from one arrested perspective, Figure 4a and 4b shows the obvious perceptual benefits of providing multiple views on the same perspective configural representation.

The utilization of the new display technics would not require that the operators be incapsulated in goggles or helmets. The small, magnetic device is probably enough to provide the necessarily data for a position dependent update of the display perspective on a few large screen monitors arranged in the visual field. This allows the operators to move around and see the perspective figures from different angles or get a central perspective from their current position by e.g. a voice command. Although some of these features might have been achieved by the use of zoom-, tilt- and rotate-functions known from CAD-systems, the continuous exposure from different perspectives is presumably important for the fast attunement to the higher-order invariants. Besides, position dependent perspective updates do not occupy a hand and do not fixate the operator to the single position of the display control device.

One important control task at the level of physical form is navigation and identification in the physical system, (cf. Table 1). The standard support for this task is technical diagrams, maps, etc. But the problem with the use of maps is their juxtaposition and the need to know their spatial orientation to support the sense of locality (Pick,

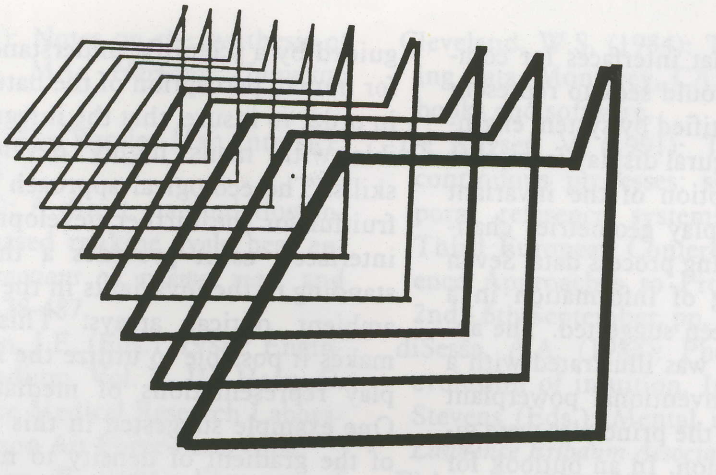

Figure 4a. From this perspective the operator gets a good view on the parts of the figures that represents the energy changes in the condenser, preheater and boiler (cf. Figure 1).

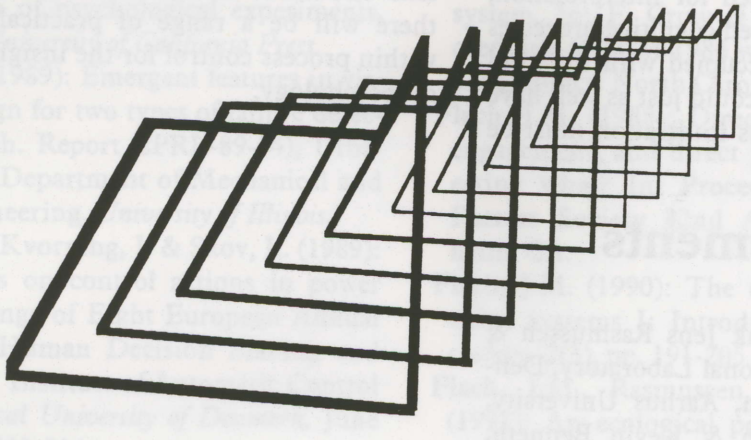

Figure 4b. This perspective makes the parts of the figure that represent the energy changes in the turbines clearly visible (cf. Figure 1).

Heinrichs, Montello, Smith, Sullivan, & Smith, in press). A person's natural knowledge of spaces is first and foremost built up when he travels through them (Kuipers, 1978). Gibson (1979) uses the term »vistas« to describe what is seen from an extended region while traveling. Vistas are serially connected; one vista closes when turning at a street corner or entering a room, and another opens up. It may be possible to improve the way-finding abilities in complex diagrams, CAD drawings and maps if they are organized as semi-naturalistic vistas. This means rooms, tunnels and gangways that bear a surface similarity to the lay-out of the real plant as the operator experiences it by direct perception. If the perspective is slaved by head movements, travelling through the vistas might be controlled manually by e.g. a joystick. This representation form will probably have to be supported with an overview map or a three dimensional model, giving a »birds eye perspective« in order to allow for fast shifts in localizations and to recover from getting lost -situations.

9 Summary and Conclusion

This article has argued that interfaces for complex dynamical systems should seek to represent the system constrains identified by system engineers in an integrated configural display form, that allows for a direct perception of the invariant system behavior from display geometries changing according to incomming process data. Seven principles for the nesting of information in a configural fashion have been suggested. The application of the principles was illustrated with a display sketch from a conventional powerplant and further arguments for the principles were given in the general discussion. In an outlook for the future it has been argued, that the new techniques emerging within virtual environments may be used to achieve a natural perspective on process displays, which changes with the head-movements of the observer.

The overall goal of ecological interface design is not to eliminate the need for interpretation, but to save the highly limited cognitive processes from being unnecessary occupied with the kind of data, that the computer could just as well have integrated graphically. This integration must be guided by a scientific understanding of the basis for human perception of the natural invironment in order to insure, that the integration is compatible with mans highly developed perceptual skills. The ecological approach seems particular fruitful for the further development of complex interfaces, as it provides a theoretical understanding of the invariants in the structures of the ambient optical arrays. This understanding makes it possible to utilize the invariants in display representations of mediated information. One example suggested in this article is the use of the gradient of density to map time over to depth. The invariant specifying time-to-contact (Lee, 1980) could be another candidate for a natural mediater of complex system information. Hopefully, this paper has clarified that ecological interface design now may have a chance to utilize some of the most important features of the invariant structures in the ambient light and that there will be a range of practical applications within process control for the insights of ecological psychology.

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References

Alexander, C. (1964): Notes on the synthesis of form. Cambridge, MA: *Harvard University Press.*

Apodaca, T. (1989): The Render Man Interface. *Byte,* 4, pp. 267-276

Beltracchi, L. (1987): A direct manipulation ingerface for water-based rankine cycle heat engines. *IEEE Transactions on sytems, man,* and *cybernetics,* 17, pp. 478-487.

Boff, K.R. & Lincoln, J.E. (Eds.) (1988): Engineering data compendium. Vol. I - III. Harry G. Amstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

Boël, M. & Daniellou, F. (1984): Elements of process control operator's reasoning: activity planning and system and response-times. In: Ergonomics problems in process operations. Institution of chemical engineers symposium series No. 90., Oxford: *Pergamon Press.* pp. 1-8.

Brunswik, E. (1956): Perception and the representative design of psychological experiments, Berkeley, CA: *University of California Press.*

Buttigieg, M.A. (1989): Emergent features in visual display design for two types of failure detection tasks. (Tech. Report EPRL-89-04), Urbana-Champaign: Department of Mechanical and Industrial Engineering, *University of Illinois.*

Bærentsen, K.B., Kvorning, J. & Skov, L. (1989): Verbal protocols on control actions in power plants. Proceedings of Eight European Annual Conference on Human Decision Making and Manual Control. Institute of Automatic Control Systems, *Technical University of Denmark,* June 12th - 14th. pp. 292-314.

Bærentsen, K.B., Kvorning, J. & Skov, L. (1989a): Verbal protocol on a routine load reduction, 11.09.1986, Stencil paper. Institute of Psychology, *University of Aarhus,* Denmark. pp. 1-21.

Carrol, J.M., & Thomas, J.C. (1980): Metaphor and the cognitive representation of computer systems. IBM Watson Research Center technical reports no. RC 8302.

Carswell, C.M. & Wickens, C.D. (1984): Stimulus integrality in display of system input-output relationships: a failure detection study. In: M.J. Alluisi (Ed.): New frontiers for science and technology: Proc. of the Human Factor Society 28th annual meeting, San Antonio.

Cleveland, W.S. (1984): The elements of graphing data. Monterey, CA: Wadsworth advanced books and software.

De Keyser, V. (1991): Temporal reasoning in continuous processes: segmentation and temporal reference systems. Proceeding at the Third European Conference on Cognitive Science Approaches to Process Control. Cardiff, 2nd - 6th September. pp. 311-334.

diSessa, A.A. (1983): Phenomenology and the evolution of intuition. In: D. Gentner & A.L. Stevens (Eds.): Mental models. Hillsdale, NJ: *Lawrence Erlbaum Associates.* pp. 15 - 34.

Fisher, S. (1982): Viewpoint dependent imaging: an interactive stereoscopic display. In: J.J. Pearson (Ed.): Proceedings of SPIE, Volume 367, Processing and display of three-dimensional data. Washington.

Fisher, S., McGreevy, M., Humphries, J., & Robinett, W., (1986): Virtual environment display system. In: F. Crow & M. Pizer (Eds.): Proceedings of ACM 1986 workshop on interactive 3D graphics. North Carolina.

Flach, J.M. (1988): Direct manipulation, direct engagement, and direct perception: what's directing what? In: Proceedings of the Human Factors Society 32nd Annual Meeting, Anaheim, CA.

Flach, J.M. (1990): The ecology of human-machine systems I: Introduction. *Ecological Psychology,* 2(3), pp. 191-205.

Flach, J.M., Rasmussen, J., & Hansen, J.P. (1991): An ecological perspective on interface design. In press.

Foley, van Dam, Feiner, & Hughes (1990): Computer Graphics. Principles and practice. Reading, Massachusetts: Addison-Wesley Publishing Company. (second edition)

Frenkel, K.A. (1988): The art and science of visualizing data. *Communication of the ACM,* 31(2), pp. 111-121.

Gaver, W. (1991): Technology Affordances. In: S.P. Robertson, G.M. Olson, & J.S. Olson (Eds.): Reaching through technology, *CHI '91 Conference proceedings, New Orleans, Louisiana.* pp. 79-84.

Gentner, D. & Gentner, D.R. (1983): Flowing waters or teeming crowds: mental models of electricity. In: D. Gentner & A.L. Stevens (Eds.): Mental models. Hillsdale, NJ: *Lawrence Erlbaum Associates.* pp. 99-129.

Gibson, J.J. (1950): The perception of the visual world. Boston: Houghton Mifflin Company.

Gibson, J.J. (1966): The senses considered as perceptual systems. Boston: Houghton Mifflin Company.

Gibson, J.J. (1979) : The ecological approach to visual perception. Boston: Houghton Mifflin Company.

Gibson, J.J. (1982): Notes on direct perception and indirect apprehension. In: E. Reed & R. Jones (Eds.): Reasons for realism. Selected essays of James J. Gibson. Hillsdale, New Jersey: *Lawrence Erlbaum Associates.* pp. 289-292.

Gibson, J.J. (1982/71): The information available in pictures. In: E. Reed & R. Jones (Eds.): Reasons for realism. Selected essays of James J. Gibson. Hillsdale, New Jersey: Lawrence Erlbaum Associates. pp. 269-283. Original in: *Leonardo,* 1971, **4**, pp. 27-35.

Gibson, Purdy & Lawrence (1955): A method of controlling stimulation for the study of space perception: The optical tunnel. *Journal of Experimental Psychology,* 50, pp. 1-14.

Goldsmith, T.E. & Svaneveldt, R.S. (1984): Facillitating multiple-cue judgments with integral information displays. In: J.C. Thomas & M.L. Schneider (Eds.): Human factors in computing systems, New Jersey: *Ablex Publishing Corporation,* pp. 243-270.

Goldwyn, R.M., Farrell, E.J., Friedman, H.P., Miller, M., & Siegel, J.H. (1973): Identifying and understanding patterns and processes in human shock and trauma. *IBM J. Res. Develop., May 1973,* pp. 230-240.

Goodstein, L.P. (1981): Discriminative display support for process operations. In: J. Rasmussen & W.B. Rouse: Human detection and diagnosis of system failures. *Plenum Publishing Corporation.* pp. 433-449.

Gould, J.D. & Lewis, C. (1985): Designing for usability: key principles and what designers think. *Communication of the ACM,* 28(3), pp. 300-311.

Hansen, J.P. (1989): Perspectives on analog interfaces. In: Proceedings of the 8'th European Annual Conference on Human Decision Making and Manual Control. Institute of Automatic Control Systems, Technical University of Denmark, June 12-14.

Hansen, J.P. (1991, in press): Spatial and temporal analog interfaces: An experimental investigation itegration and temporal information. Paper submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Psychology in the University of Århus, Denmark, 1991.

Hansen, J.P., Løvborg, L., & Rasmussen, J. (1991): Simulation of cognitive behavior in computer games. Proceeding of the second MOHAWCK workshop. In press.

Hester, M. (1977): Visual attention and sensibility. In: R. Shaw & J. Bransford (Eds.): Perceiving, acting, and knowing. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Hettinger, L.J., Kennedy, R.S., & Rico, G.E. (in press): Motion sickness: Ecological perspectives. In J. Flach et. al. (eds): The ecology of man-mashine systems.

Hollan, J.D., Hutchins, E.L., & Weitzman, L. (1984): Steamer: an interactive inspectable simulation-based training system. *The AI magazine,* **4**, pp. 15-27.

Johansson, G., Von Hofsten, C., & Jansson, G. (1980): Event perception. *Annual review of psychology,* **31**, pp. 27-63.

Kirlik, A., Miller, R.A., & Jagacinski, R.J. (1988): Route planning as a perceptual task. In: Proceedings of the 23rd Annual conferance on Manual Control, Cambridge, MA.

Kleer, J. & Brown, J.S. (1983): Assumptions and ambiguities in mechanistic mental models. In: D. Gentner & A. L. Stevens (Eds.): Mental models. Hillsdale, NJ: *Lawrence Erlbaum Associates.* pp 155-190.

Knak, C. (1982): Stationære kraftanlæg. Copenhagen: G.E.C. Gads forlag. (in danish)

Kuipers, B. (1978): Modelling spatial knowledge. *Cognitive science,* 2, pp. 129-153.

Lakoff, G. and Johnson, M. (1980): Methaphors we live by. Chicago: University of Chicago Press.

Lee, D.N. (1980): The optic flow field: the foundation of vision. *Phil. Trans. R. Soc. Lond.,* **B. 290**, pp. 169-179.

Leplat, J. & Rocher, M. (1984): Ergonomics of the control of simultaneous process: case study in biochemical industry. In: Ergonomics problems in process operations. Institution of chemical engineers symposium series No. 90., Oxford: Pergamon Press.

Lindsay, R.W. and Staffon, J.D. (1988): A model based display system for the experimental breeder reactor-II. Paper presented at the joint meeting of the American Nuclear Society and the European Nuclear Society, Washington, DC.

McCloskey, M. (1983): *Intuitive Physics. Scientific American,* **4**, pp. 114-122.

Mestre, D., Peruch, P., Savoyant, A., & Pailhous, J. (in press): From Locomotion to teleoperation: The design of ecological interfaces. In J. Flach et. al. (eds): The ecology of man-mashine systems.

Norton, D., & Stark, L. (1972): Eye movements and visual perception. In: Perception: Mechanisms and models. San Francisco: W.H. Freeman and Company.

Pausch, R. (1991): Virtual reality on five dollars a day. In: S.P. Robertson, G.M. Olson, & J.S. Olson (Eds.): Reaching through technology, *CHI '91 Conference proceedings, New Orleans, Louisiana.* pp. 265 - 270.

Pick, H.L., Heinrichs, M., Montello, D., Smith, K., Sullivan, C., & Smith, W. (in press): Topographic map reading. In J. Flach et. al. (eds): The ecology of man-mashine systems.

Pomerantz, J.R. (1986): Visual form perception: an overview. In: H.C. Nusbaum, & E.C. Schwab (Eds.): Pattern recognition by humans and machines. Vol. 2. Visual perception. Orlando, Florida: Academic Press, Inc.

Rasmussen, J. (1986): Information processing and human-machine interaction: an approach to cognitive engineering. New York: North-Holland.

Rasmussen, J. (1988): A cognitive engineering approach to the modellig of decision making and its organization in process control, emergency management, CAD/CAM, office systems, library systems. In: W.B. Rouse (Ed.): Advances in man-machine system research, Vol. 4. J.A.I. Press.

Rasmussen, J. & Goodstein, L.P. (1988): Information technology and work. In: M. Helander (Ed.): Handbook of human-computer interaction. Amsterdam: *Elsevier Science Publishers B.V.*, pp. 175-201.

Rasmussen, J. & Pejtersen, A.M. (in press): Taxonomies of work domains. In J. Flach et. al. (eds): The ecology of man-mashine systems.

Rasmussen & Vicente (1989): Coping with human errors through system design: implications for ecological interface design. *Int. J. Man-Machine Studies*, **31**, pp. 517-534.

Rasmussen & Vicente (1990): Ecological interfaces: a technological imperative in high tech systems? *International Journal of Human computer Interaction*, **2(2)**, pp. 93-111.

Sanderson, P.M., Flach, J.M., Buttigieg, M.A., & Casey, E.J. (1989): Object displays do not always support better integrated task performance. *Human Factors*, **31(2)**, pp. 183-198.

Senders, J.W. (1966): A re-analysis of the pilot eye-movement data. *IEEE Transactions on human factors in electronics.* 7(2), pp. 103-106.

Smets et al. (i press): The theory of direct perception and telepresence. In J. Flach et. al. (eds): The ecology of man-mashine systems.

Spelke, E.S. (1990): Principles of object perception. *Cognitive Science*, **14**, pp. 29-56.

Stark, L., & Ellis, S.R. (1981): Scanpaths revisited: cognitive models direct active looking. In: D.F. Fisher, R.A. Monty, & J.W. Senders: Eye movements: cognition and visual perception. Hillsdale, New Jersey: *Lawrence Erlbaum Associates*, pp. 193-226.

Tufte, E.R. (1983): The visual display of quantitative information. Cheshire, Connecticut: Graphics Press.

Tufte, E.R. (1990): Envisioning information. Cheshire, Connecticut: Graphics Press.

van Nes, F.L. (1972): Determining temporal differences with analogue and digital time displays. *Ergonomics*, **15(1)**, pp. 73-79.

Veniar, F. (1948): Difference thresholds for shape distortion of geometrical squares. *Journal of Psychology*, **26**, pp. 461-476.

Vicente, K.J., & Rasmussen, J. (1990): The ecology of human-machine systems II: mediating »direct perception« in complex work domains. *Ecological Psychology*, **2(3)**, pp. 207-249.

Vicente, K.J. (1991): Supporting knowledge-based behavior through ecological interface design. Thesis. Urbana-Champaign: Department of Mechanical and Industrial Engineering, University of Illinois.

Warren, W. (in press): Environmental design as the design of affordances. In J. Flach et. al. (eds): The ecology of man-mashine systems.

Wickens, C.D., & Andre, A.D. (1990): Proximity compatibility and information display: Effects of color, space, and objectness on information integration. *Human Factors*, **32(1)**, pp. 61-67.

Winograd, T., & Flores, F. (1986): Understanding computers and cognition: a new foundation for design. Norwood, New Jersey: Ablex publishig corporation.

Woods, D.D. (1984): Visual momentum: a concept to improve the cognitive coupling of person and computer. *Int. J. Man-Machine Studies*, **21**, pp. 229-244.

Woods, D.D. (in press): The cognitive engineering of problem representations. In: J. Alty & G. Weir: Human-computer interaction on complex systems. London: Academic Press.

Woods, D.D., & Roth, E.M. (1988): Cognitive systems engineering. In: M. Helander (Ed.): Handbook of human-computer interactions. Amsterdam: *Elsevier Science Publishers.* pp. 3-43.

Zusne, L. (1970): Visual perception of form. New York: Academic Press.

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Gibson's (1979) theory on direct perception forms the basis of an ecological approach to interface design. The paper argues that interfaces for complex dynamical systems should seek to represent the system constrains identified by system engineers in an integrated configural display form, that allows for a direct perception of the invariant system behavior from display geometries changing according to incomming process data. Seven principles for the nesting of information in a configural fashion are suggested. The application of the principles is illustrated with a display sketch from a conventional power plant and further arguments for the principles is given in a general discussion.

In particular, the configural interface should integrate information on the system evolution over time, the objective clock time and a symbolic representation of the system functions. This integration is achieved in a new display format, the time tunnels, revealing process invariants and changes as symmetry or asymmetry in figural patterns over depth. In an outlook for the future it is suggested, that the new techniques emerging within virtual media environments may be used to achieve a natural perspective on process displays, changing with the head movements of the observer.

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